BELLCOMM, INC.

SUBJECT: Magnetic and/or Electrostatic Shielding of Spacecraft Case 600-4

DATE: March 20, 1967

FROM: F.G. Allen

ABSTRACT

The shielding of a spacecraft from harmful radiation by use of magnetic fields, electrostatic fields or a combination of the two is briefly reviewed from a feasibility viewpoint. Shielding against the most damaging components of trapped radiation in the Van Allen belts - 0.2 to 2 Mev electrons, appears feasible with magnetic shielding using superconductors cryogenically cooled. Electrostatic shielding from electrons is probably impossible because of field emission from a negative spacecraft. Pure electrostatic shielding by a positive spacecraft potential against energetic protons results in a collected electron radiation hazard worse than that due to the protons. An ambitious proposal combining both electrostatic and magnetic shielding to protect against 200 Mev protons as well as electrons is described.

(NASA-CR-153755) MAGNETIC AND/OR ELECTROSTATIC SHIELDING OF SPACECRAFT (Bellcomm, Inc.) 9 p

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MEMORANDUM FOR FILE

Introduction

The principal components of radiation against which it is difficult to shield astronauts in spacecraft using mass absorbers alone, are charged particles.(1) These are chiefly trapped electrons and protons within the Van Allen belts and galactic or solar cosmic ray protons in the outer portion of the earth's magnetosphere and beyond. It is thus natural to inquire as to the feasibility of shielding against such charged particles by magnetic or electric fields purposely set up around the spacecraft. The following is a very brief review of the physical principles, the limitations, and the present status of programs to test or develop such systems.

Magnetic Shielding

The force exerted on a particle of charge e moving with velocity v normal to a magnetic field H is given by

$$F = evH/c \tag{1}$$

which leads to a radius of curvature of the path of

$$r = \frac{mvc}{eH} = \frac{pc}{eH} \tag{2}$$

where m is particle mass, c the velocity of light, and p the momentum.

Taking account of the relativistic mass increase for electrons above 1 Mev, the solution becomes

$$r = (E^2 + 2EE_o)^{1/2}/He \tag{3}$$

where E is kinetic energy and $E_o = m_o c^2$ is the rest mass.

Solutions of (3) are shown in Table I for typical magnetic fields and energies for electrons and protons. It is seen that, since electrons with energies up to several Mev are bent with curvatures of a few meters by fields of a few hundred gauss, such fields maintained around a spacecraft could give significant protection from the trapped electrons within the Van Allen belts. (This includes synchronous orbits at 37,000 KM.) Estimates of the mass and power required to set up such fields indicate that they would be excessive unless the conducting coils are superconducting, (2,3,4). To give optimum protection the magnetic flux lines should be everywhere parallel to the spacecraft surface; this could be achieved only with a toroidal spacecraft. However, a compromise could be made by placing heavy shielding at those locations where flux lines penetrate the surface, as at the north and south poles of a dipole configuration.

Note from the table that 500 gauss fields would deflect 0.1 Mev protons in the vicinity of the spacecraft (r = 1 meter) but that 100 Mev protons could only be deflected by fields in excess of 10,000 gauss; weight estimates for such a system (3) even using superconductors, are prohibitive, (though comparable to solid shielding).

We note two advantages of magnetic shielding before passing on: 1) both positive and negative particles are deflected by the same field configuration; 2) fields of a few hundred gauss should cause astronauts no hazards during EVA provided magnetic materials are avoided.

One problem that must be considered with magnetic shielding will be the torque set up by the strong spacecraft dipole acting against any ambient magnetic field. Within the earth's magnetosphere such torques can become comparable to gravity gradient torques (many pound-feet) and hence appreciable energy must be expended to maintain any attitude other than that dictated by the earth's field. On the other hand, this same effect could be useful in some instances where the magnetic alignment of the spacecraft is acceptable for experiments or operations to be performed.

Electrostatic Shielding

A spacecraft charged electrostatically to a potential V relative to its environment will repel all charged particles of like polarity with energy less than $V \cdot e$. Thus a spacecraft at -2MV would repel all electrons of energy less than that, and a spacecraft at +200MV would repel all protons with energies below 200 Mev.

There are several major disadvantages that make pure electrostatic shielding appear infeasible. First, while charges of like polarity are repelled, particles of opposite polarity are attracted and their energy at impact is increased by the potential of the spacecraft. Thus, if one tried to shield against 200 Mev protons by holding the spacecraft at +200 MV, a large flux of electrons with energies of 200 Mev and over would result, causing a new radiation problem worse than the first; (Brems strahlung results which is harder to shield against than protons).

Second, it will probably be impossible to produce negative potentials on the spacecraft sufficiently large to give protection. This is due to the fact that electrons are field-emitted from a negative electrode into vacuum with an exponentially rising current-voltage law from all sharp corners when local fields exceed 2×10^7 volts/cm. Since the field goes as V/a where a is the radius of the corner, field emission starts spontaneously from most objects at a few tens of kilovolts. While a carefully designed electrode with all corners polished and having radii of many centimeters could withstand megavolts, a manned spacecraft with antennas, hatches, thrusters, etc. protruding, could not.

Third, the power needed to maintain a large positive potential on the craft to shield against protons would be very large under most circumstances. This power is computed from the current of electrons attracted to the spacecraft times spacecraft potential, since the latter must be overcome to re-eject the collected electrons and maintain the potential. Since electron velocities are at least 10 times higher than spacecraft velocities even in the ionosphere, this current can be calculated as (Spacecraft area) x (incident electron flux) x (enchancement factor). The enhancement factor is a measure of the extent of the potential of the spacecraft around it in space and its effectiveness in trapping charges of given energies. While a regorous solution is difficult, this factor may vary from a few times unity to over 100 for different situations (5,6).

We can now use the above relation to estimate the power drain required to hold a spacecraft at a high positive potential, say 200 megavolts. We consider three different altitudes: 1) For the ionosphere, at altitudes near 200 KM, assume 10^5 electrons/cc and electron velocitites of 2×10^7 cm/sec (corresponding to a temperature of 1000^oK). Then electron flux is 2×10^{12} cm^{-2} sec^{-1}. For a spacecraft area of 10^5 cm^2 and an assumed enhancement factor of 10 we find a total current flow of 0.3 amperes or a power drain of 60 megawatts!

At synchronous altitude (37,000 KM) the ionospheric contribution has dropped to a few H^+ ions and free electrons/cc (7), and the only spacecraft flux that need be considered is that due to trapped electrons or protons. (The solar wind is still excluded by the magnetosphere.) While these trapped fluxes vary greatly in time and in latitude, a very rough estimate of the total trapped electron flux at 6.6 earth radii would be $J = 10^7$ to 10^8 cm^{-2} sec^{-1} (8). This yields a total current of 30 microamperes or a total power of about 6 kilowatts to hold the spacecraft at 200 megavolts. This is not totally unreasonable to attempt.

Similar calculations for orbits at higher altitude above the magnetosphere, where the solar wind provides a flux of electrons of $\sim 10^9$ cm^{-2} sec^{-1} (5,9) lead to power levels about ten times higher than those in synchronous orbit.

The above calculations have assumed that each collected electron accounts for only one negative charge reaching the spacecraft. However, the leakage of gas from the spacecraft surrounds it with an atmosphere of neutral gas particles whose density may correspond to pressures as high as 10^{-5} Torr instead of the 10^{-12} to 10^{-14} Torr one might otherwise expect at high orbit (10). High energy electrons will thus ionize many gas molecules on their way to the spacecraft surface, (especially if put into helical paths by a magnetic field as well). All electrons resulting will be collected while positive ions will be expelled. This ionization process is also enchanced by ultra-violet solar radiation. The result will be a large enhancement of collected electron current over those calculated above.

Finally, electrostatic shielding could be hazardous if continued during astronaut EVA. Even though the capacitance of an astronaut to free space is small, very large differences in potential between astronaut and spacecraft would be set up. To transfer sufficient charging current to bring the astronaut back to spacecraft potential upon contact when hundreds of megavolts are involved, could cause injury.

Combined Magnetic and Electrostatic Sheilding

A prposal made in 1964 (3) to combine the two methods is being actively pursued through an AVCO EVERETT contract with NASA/OART (11). Magnetic shielding would protect against electrons and the spacecraft would be electrostatically charged positively to 100 or 200 Mev to protect against cosmic protons. Since electron flux to the spacecraft is prevented by the magnetic shield, power drain should be minimal, and no increased radiation due to Brems-strahlung from collected electrons is involved.

The authors of this proposal have pointed out that under ideal conditions, the electrostatic charge could be set up simultaneously with the magnetic field, using the expanding magnetic field lines to help eject electrons. Then both should remain, with no further energy needed, for a time that is hoped to be long enough to outlast a solar flare event. If so, a very complex 200 Mev Van de Graaf generator would not be needed to expel the electrons. (It may well be argued that this system itself is more difficult to build than a Van de Graaf generator!).

While direct discharge due to trapped electron flux is minimized by the magnetic shield, discharge by ionization of the gas about the spacecraft now predominates. Rough estimates indicate that this discharge will be too rapid for this latter method (one shot establishment of magnetic and electrostatic fields) to be useful unless the neutral gas concentration around the spacecraft is less than about 10^{-12} Torr. Since present (Apollo) specified leak rates provide pressures about 10^6 to 10^7 times this value, the method would be impossible unless a new generation of vacuum tight spacecraft is developed.

This scheme is very far from being demonstrably workable. For example, potentials of over 15 megavolts cannot yet be maintained on electrodes on earth. Furthermore, severe problems in plasma containment by the magnetic field may be encountered. However, it does have attractive features which neither magnetic nor electrostatic methods by themselves provide.

A second project is currently underway at MSFC, also through OART (11) to look at hardware feasibility of shielding in actual spacecraft designs; only magnetic shielding has been considered thus far.

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1011-FGA-rpk F. G. Allen

Attachment
"Table I" "Radius of Curvature in Meters, for Electrons and Protons of Energy E, in Magnetic Field H"

Bibliography

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The trapped electrons are found in the Van Allen belts at altitudes above 150 KM out to the boundary of the earth's magnetosphere at about 10 earth radii, or 60,000 KM. They range in energy from a few tenths to several million electron volts, with maximum fluxes of up to 10^9/cm^2/sec with energies greater than 500 KeV at 15,000. to 20,000. KM. Trapped energetic protons are found in the inner Van Allen belt, where proton fluxes reach maxima of 10^4 protons/cm^2/sec with energies greater than 40 MeV at an altitude of 10,000 KM. The principal proton hazard, however, comes from very high energy cosmic ray protons near the outer edge of the magnetosphere and beyond, where galactic fluxes exist all the time of several protons/cm^2/sec with energies greater than 100 MeV. During major solar events, solar protons fluxes can exceed these galactic intensities by 10 to 1000 times during many hours.

A good summary of all these space radiation characteristics is given in Natural Environment and Physical Standards for the Apollo Program, April, 1965, and revisions, NASA.

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TABLE I

RADIUS OF CURVATURE IN METERS, FOR ELECTRONS AND PROTONS
OF ENERGY E, IN MAGNETIC FIELD H

ELECTRONS

H	E = 0.1 Mev	E = 1 Mev	E = 10 Mev	E = 100 Mev
10 gauss	1.1 m	4.7 m	35.m	330. m
100 gauss	0.1	.47	3.5	33.
1000 gauss	0.01	.047	0.35	3.3

PROTONS

10 gauss	47.5 m	150.m	475. m	1500. m
100 gauss	4.7	15.	47.	150
1000 gauss	0.4	1.5	4.	15.